Truck Platooning Early Deployment – Independent Evaluation

Requirements for Performance Measures

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Sampson Asare, James Chang, and Barbara Staples	
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16. Abstract

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term services is truck platooning. Truck platooning promises fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. In the future, the commercial trucking industry is planning to deploy vehicle-to-vehicle based truck platooning systems. System-wide impacts and the impact on truck drivers, fleet owners, and light duty vehicle drivers still need to be assessed for operational and safety impacts. To this end, the USDOT selected three teams (Battelle, California PATH, and CDM Smith) to participate in "Truck Platooning Early Deployment Assessment, Phase 1" project. The objective of Phase 1 is to develop a concept and proposal for deploying and assessing a commercial truck platoon system. Field test deployment and assessment will occur in Phase 2.

Noblis has been tasked by the Federal Highway Administration (FHWA) as the Phase 1 Independent Evaluator (IE) to provide evaluation-related technical support to the three teams as they develop their Phase 1 deliverables. The purpose of this report is to present requirements for performance measures that were developed for 8 key areas by the IE with inputs from FHWA, National Highway Traffic Safety Administration (NHTSA), Federal Motor Carrier Safety Administration (FMCSA), and the Department of Energy (DOE). The report includes:

- Requirements for performance measures to guide the development of performance measures and evaluation plans by Phase 1 Awardees, and eventually the evaluation of Phase 2 field test(s); and
- Levels of priority associated with each of the developed requirements based on the objectives of this project.

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Executive Summary

Background

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term applications is truck platooning. Truck platooning promises fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. The Federal Highway Administration (FHWA) as part of the Exploratory Advanced Research (EAR) program funded exploratory research to assess and study two and three truck platooning technologies and operations (FHWA, EAR Program). In the future, the commercial trucking industry is anticipating the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts and the impact on truck drivers, fleet owners, and light duty vehicle drivers still needs to be assessed for operational and safety impacts.

In order to understand the potential impacts of truck platooning systems, FHWA issued a Broad Agency Announcement (BAA) on August 30, 2018 to conduct a multi-state, long-haul field test of truck platooning operations with similar trucks (e.g., same fleet, size, and make/model) with minimum SAE Level 1 automation capabilities. The "Truck Platooning Early Deployment Assessment" project is divided into two phases. The objective of Phase 1 is to develop a concept and proposal that sets the stage for an assessment of a commercial vehicle platooning field operational test that has an observable and measurable near-term impact. The field test deployment and assessment will occur during Phase 2 of the project. This project is expected to help answer research questions related to human factors impacts on truck drivers, interactions between truck platoons and surrounding traffic, fleet operator impacts, fuel efficiency, policy, and other potential impacts. Three teams were selected by FHWA to participate in the 9-month Phase 1 project (hereafter referred to as Phase 1 Awardees). The Awardee teams are led by Battelle, California PATH, and CDM Smith. Only Phase 1 Awardees (i.e., Battelle, CDM Smith, and California PATH) will be eligible to submit Phase 2 proposals.

An Independent Evaluator (Noblis Inc.) was selected by ITS JPO to provide technical support to Phase 1 Awardees on how to plan and evaluate their truck platoon field deployments. Among the responsibilities of the Phase 1 Independent Evaluator (IE) is the need to define requirements for performance measures for 8 key areas of interest that will be used by both the IE, and Phase 2 teams, to

evaluate the performance of truck platooning systems tested as part of an early deployment.

Requirements Development Approach

An iterative approach in which inputs were solicited from multiple stakeholders was used to develop the requirements for performance measures. Firstly, the IE developed an initial set of performance measure requirements based on general knowledge of truck platoon technology as well as Awardee's Phase 1 documents. The initial performance measure requirements were reviewed by stakeholders from FHWA, National Highway Traffic Safety Administration (NHTSA), Intelligent Transportation Systems Joint Program Office (ITS JPO), Federal Motor Carrier Safety Administration (FMCSA), and the Department of Energy (DOE) to ensure they captured the different areas of interest. Feedback from the federal stakeholders was used to revise the performance measure requirements. This was followed by a webinar hosted by the IE to walk the Phase 1 Awardees through the revised performance measure requirements. The webinar afforded Phase 1 Awardees the opportunity to ask clarifying questions and provide feedback on the revised requirements prior to finalization. In addition to verbal feedback during the webinar, Phase 1 Awardees submitted written comments after detailed review of the revised performance measure requirements. Both the verbal and written feedback from Phase 1 Awardees were used to develop the final requirements for performance measures.

The requirements were categorized into groups based on the 8 key areas identified by the FHWA in the BAA. The 8 key areas and their abbreviations (as used in the rest of this report) are as shown below:

- Platoon Operational Characteristics (OP) – This includes the formation, operation, reconfiguration, and termination of a platoon.
- Safety (S) – This include aspects of driver and vehicle performance that impact safety, as well as interactions with surrounding traffic.
- Mobility (M) – This includes impacts on congestion and traffic flow, including constraints imposed by temporary or permanent roadway environment characteristics (e.g., work zones, merge areas, incidents, weather conditions, etc.).
- Energy and Emissions (EE) – This includes potential for fuel savings and accompanying reductions in emissions and release of pollutants
- Fleet Operator and Driver Impacts (FLT) – This includes impacts on driver training, driver performance, fatigue, workload, and attention, operational costs
- Infrastructure Impacts (II)– This includes identification of infrastructure characteristics and requirements that would support safe and extended performance of truck platoons

- State and Local Government Impacts (SL) – This includes impacts to maintenance and operations costs, inspection programs, enforcement procedures, driver licensing, policies associated with platooning operations, etc.
- Vehicle Equipment Design Implications (VED) – This includes vehicle and vehicle equipment needs introduced by the use of truck platooning systems.

Prioritization of Requirements

Based on feedback from Phase 1 Awardees as well as potential funding limits for Phase 2 of this project, there was a need to assign priority levels to each of the requirements developed for performance measures. In this project, prioritization deals with relative importance of the many requirements developed. That is, per the goals and objectives of this project, some requirements merit attention (i.e., need to be addressed) before other competing requirements are attended to (if budget and time allows). The prioritization of requirements in this project was based on the preference of the ITS JPO and its partner agencies (primarily FHWA, NHTSA, FMCSA, and DOE) in terms of value of the insights associated with the respective requirements. Three main priority levels were defined, and each requirement was assigned one of these priority levels. The three priority levels and their general definitions are as follows:

- **Most Important:** If a requirement for performance measure(s) is assigned "most important" priority, it implies that developing performance measures to satisfy those requirements is of topmost priority. In other words, ITS JPO and its partner agencies (primarily FHWA, NHTSA, FMCSA, and DOE) expect to gain valuable insights regarding that aspect of truck platooning from this project.
- **Important:** A requirement for performance measure(s) with "important" designation implies consideration should be given to developing performance measures to satisfy that requirement. While insights from requirements in this priority level are valuable, they are of a second level of importance.
- **Desirable:** A requirement for performance measure(s) with "desirable" priority level implies that performance measures may be developed for such requirement; however, they are "nice-to-haves" and not of highest value as far as this project is concerned. Performance measures in this category are worthwhile if minimal effort is required to collect data and estimate them.

Although each requirement was assigned a priority level, the Awardees have the flexibility to choose which of the requirements they intend to satisfy in Phase 2. The decision on which requirements to satisfy will depend on factors such as Awardees' proposed truck platooning concept, data collection capability, cost of developing performance measure(s) to satisfy requirements versus value trade-off, etc. Also, there is no restriction on the number of requirements or mix of requirements (i.e., considering priority levels) that Awardees must satisfy.

Conclusions

This report is an outcome of the Phase 1 IE's support to the USDOT on the "Truck Platooning Early Deployment Assessment, Phase 1" project. The report includes:

- Requirements for performance measures to guide the development of performance measures and evaluation plans thereof by Phase 1 Awardees, and eventually the evaluation of Phase 2 field test(s); and
- Levels of priority associated with each of the developed requirements based on the goals and objectives of this project.

While the requirements for performance measures developed in this project can be used to guide performance evaluation of other truck platooning projects, it is imperative that they are adapted to suit the specific goals and objectives of the individual project. However, the priority levels associated with performance measure requirements must be developed from scratch based on the specific goals and objectives of the individual project.

1 Introduction

The United States Department of Transportation (USDOT) recognizes that cooperative automated driving systems will have a transformative impact on how the nation's highways will operate in the future. One of the proposed near-term applications is truck platooning. Truck platooning promises fuel savings to platooning trucks by enabling them to follow each other more closely, while still in a safe manner. The Federal Highway Administration (FHWA) as part of the Exploratory Advanced Research (EAR) program funded exploratory research to assess and study two and three truck platooning technologies and operations (1). In the future, the commercial trucking industry is anticipating the deployment of truck platooning systems based on vehicle-to-vehicle (V2V) communications. System-wide impacts, the impact on truck drivers, fleet owners, and light duty vehicle drivers still needs to be assessed for operational and safety impacts.

In order to understand the potential impacts of truck platooning systems, FHWA issued a Broad Agency Announcement (BAA) on August 30, 2018 to conduct a multi-state, long-haul field test of truck platooning operations with similar trucks (e.g., same fleet, size, and make/model) with minimum SAE Level 1 automation capabilities. The "Truck Platooning Early Deployment Assessment" project is divided into two phases. The objective of Phase 1 is to develop a concept and proposal that sets the stage for an assessment of a commercial vehicle platooning field operational test that has an observable and measurable near-term impact. The field test deployment and assessment will occur during Phase 2 of the project. Specific research questions to be answered include:

- What are the human factors impacts on truck drivers in long-haul operation of a truck platoon?
- How are the other road users' behavior impacted in the presence of truck platoon operations (e.g., highway entry/exit points, visibility, signage, etc.)?
- How does the gap between the trucks impact the costs / benefits of platooning (fuel saving, safety, operating costs, vehicle maintenance, mobility/travel time) as well as the risks (number of cut-ins, truck driver's behavior/acceptance/fatigue)?
- What are the benefits of truck platooning to fleet owners?
- What are the policy, operational and safety impacts of truck platooning?

Three teams were selected by FHWA to participate in the 9-month Phase 1 project (hereafter referred to as Phase 1 Awardees). The Phase 1 Awardee teams are led by Battelle, California Partners for Advanced Transportation Technology (PATH), and

CDM Smith (2). Only the Phase 1 Awardees will be eligible to submit Phase 2 proposals.

Noblis was awarded a contract to support ITS JPO and its partner agencies (primarily FHWA and FMCSA) as the Independent Evaluator (IE) for Phase 1 of this project. The role of the IE in Phase 1 is to:

- Define requirements for performance measures that will be used by both the independent evaluator, and Phase 2 teams, to evaluate the performance and impacts of truck platooning systems tested as part of an early deployment. Note that the IE will not develop performance measures; rather, Phase 1 Awardees will use the requirements defined by the IE to develop performance measures for their proposed truck platoon deployments.
- Plan and conduct outreach and coordination events with Phase 1 Awardee teams to provide guidance and offer an opportunity for feedback and questions around performance measure and evaluation methodology development.
- Support Phase 1 Awardee teams to identify performance measures and data requirements; procedures to collect, store, manage, and provide access to data; and evaluation plans.

The above expectations are limited to only the Phase 1 IE. The IE for Phase 2 and corresponding role has not yet been determined.

1.1 Truck Platooning Technology Basics

Truck platooning uses technology, including V2V wireless communication, to allow trucks to follow each other safely and more closely than conventional driving. For example, using V2V communications, two trucks in a platoon can “electronically couple” such that any initiation of braking by the lead truck can instantaneously be initiated by following trucks (without truck driver intervention). Truck platooning technology can be classified as a cooperative automated vehicle (AV) system because it uses both on-board systems plus communications between trucks to provide information critical to driving. The role of the truck driver in a following truck is dependent on the level of automation incorporated into the truck platooning technology. According to the Society of Automotive Engineers (SAE) J3016 standard, there are 6 levels of driving automation (numbered 0 through 5) (3). For this project, Awardees are required to propose and deploy cooperative automated truck platooning system with minimum SAE Level 1 automation capabilities. The first three SAE levels of driving automation are briefly described below.

- Level 0 (No driving Automation) – The human driver is fully in charge of the entire driving task.

- Level 1 (Driver Assistance) – The human driver is in charge of either the longitudinal vehicle motion control or lateral vehicle motion control. At this level, both longitudinal and lateral vehicle controls cannot be automated. It is also expected that the human driver performs the remainder of the driving task (e.g., observing roadway driving conditions, detection of roadway hazards, etc.).
- Level 2 (Partial Driving Automation) – The automation system is in charge of both longitudinal and lateral vehicle control. This allows for both hands-off (from steering wheel) and feet-off (from accelerator and brake) driving. However, the human driver is expected to perform the remainder of the driving task (e.g., observing roadway driving conditions, detection of roadway hazards, etc.).

1.2 Purpose of the Report

The purpose of this report is to define requirements for performance measures that will be used by both the Phase 2 IE, and Phase 2 teams, to evaluate the performance of truck platooning systems tested as part of an early deployment.

1.3 Requirements Development Approach

An iterative approach in which inputs were solicited from multiple stakeholders was used to develop the requirements for performance measures. Firstly, the Phase 1 IE developed an initial set of performance measure requirements based on general knowledge of truck platoon technology, Awardee's Phase 1 documents, and the 8 key areas of interest outlined in the BAA. The initial requirements for performance measures were reviewed by stakeholders from ITS JPO, FHWA, Federal Motor Carrier Safety Administration (FMCSA), National Highway Traffic Safety Administration (NHTSA) and the Department of Energy (DOE) to ensure they capture the different areas of interest. Feedback from the federal stakeholders was used to revise the initial requirements for performance measures. This was followed by a webinar hosted by the IE to walk the Phase 1 Awardees through the revised performance measure requirements. The webinar afforded Phase I Awardees the opportunity to ask clarifying questions and provide feedback on the revised requirements prior to finalization. In addition to verbal feedback during the webinar, Phase 1 Awardees submitted written comments after detailed review of the revised performance measure requirements. Both the verbal and written feedback from Phase 1 Awardees were used to develop the final requirements for performance measures.

1.4 Organization of the Report

This report is organized as follows:

- The first Chapter provides background information about the Truck Platooning Early Deployment Assessment project, purpose of the report and requirements development approach;
- Chapter 2 describes the requirements for performance measures developed for this project; and
- Chapter 3 presents conclusions for this report.

2 Requirements for Performance Measures

As part of its role, the Phase 1 IE developed a set of requirements to guide the development of performance measures and evaluation plans thereof by Phase 1 Awardees, and eventually the evaluation of Phase 2 field test(s). The requirements were categorized into groups based on the 8 key areas of interest identified by FHWA in the BAA. The 8 key areas and their abbreviations (as used in the rest of this report) are as shown below:

- Platoon Operational Characteristics (OP) – This includes the formation, operation, reconfiguration, and termination of a platoon.
- Safety (S) – This include aspects of driver and vehicle performance that impact safety, as well as interactions with surrounding traffic.
- Mobility (M) – This includes impacts on congestion and traffic flow, including constraints imposed by temporary or permanent roadway environment characteristics (e.g., work zones, merge areas, incidents, weather conditions, etc.).
- Energy and Emissions (EE) – This includes potential for fuel savings and accompanying reductions in emissions and release of pollutants
- Fleet Operator and Driver Impacts (FLT) – This includes impacts on driver training, driver performance, fatigue, workload, and attention, operational costs
- Infrastructure Impacts (II)– This includes identification of infrastructure characteristics and requirements that would support safe and extended performance of truck platoons
- State and Local Government Impacts (SL) – This includes impacts to maintenance and operations costs, inspection programs, enforcement procedures, driver licensing, policies associated with platooning operations, etc.
- Vehicle Equipment Design Implications (VED) – This includes vehicle and vehicle equipment needs introduced by the use of truck platooning systems.

The remainder of this Chapter presents the requirements developed for each of the 8 key areas of interest. For each requirement, there is a unique identifier (ID) that is prefixed by the key area it belongs to, followed by the requirement number for that key area. For example, OP-001 is interpreted as requirement number one in the Platoon Operational Characteristics key area. In addition, explanatory notes highlighting the reasons behind each requirement is provided. It should be

noted that there can be overlap across key areas; that is, a requirement may be applicable to more than one key area. In such instances, the requirement is listed only once instead of repeating it for all applicable key areas.

2.1 Platoon Operational Characteristics

Truck platoon formation can occur through ad hoc means (i.e., truck drivers on the road decide to platoon without prior planning/arrangement), local coordination (i.e., coordinated by fleet dispatch operations center or third party service while trucks are on the road), and scheduled coordination (i.e., platoon formation pre-planned before trucks get on the road). Once platoons are formed, trucks will remain in platoon mode until platoon is dissolved as a result of many factors (e.g., cut-ins by unequipped vehicles, platoon splits, truck driver disengagement due to external conditions, etc.) Because cut-ins are inevitable, the platoon system needs to be designed to automatically handle a cut-in. Performance measures for this key area should be able to capture the dynamics of truck platoon operations. The requirements for performance measures developed for this key area is as shown below in Table 2-1.

Table 2-1. Requirements for Platoon Operational Characteristics Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
OP-001	Performance measure(s) should capture how long it takes for truck platoon to be formed based on the choice of coordination strategy being used and other factors.	This requirement ensures that measure(s) are developed to measure the time from when one or more trucks start (which may be defined in different ways suited to the system design and planned operational approach for the fleet) to when platoon is successfully formed. The choice of coordination strategy (e.g., ad-hoc, local coordination, global coordination) and other factors may influence amount of time required for truck platoon to be formed. This requirement is necessary because the amount of time it takes for a platoon to be formed may affect platoon productivity as well as surrounding traffic. More than one coordination strategy may be used in a single trip.

ID	REQUIREMENT	EXPLANATION NOTES
OP-002	Performance measure(s) should capture general behavior of trucks/drivers (e.g., speeding behavior, lane changing behavior, etc.) as they seek to form a platoon.	This requirement ensures that performance measures are developed to measure how trucks/drivers behave in their attempt to platoon. These include speeding behavior (e.g., does the following truck overspeed to join the lead truck), lane changing behavior (e.g., do trucks make risky lane changes in order to platoon) and others.
OP-003	Performance measure(s) should capture the usage rate of truck platoon system categorized with respect to different conditions/factors encountered during trips.	This requirement ensures that measure(s) are developed to measure the usage rate of trucks traveling in platoon mode (capturing the mode and gap settings, if applicable). This provides an estimate of how often trucks equipped with the platoon technology actually platooned during a trip. Different conditions may include weather, traffic regimes (e.g., different levels of congestion), work zones, and other applicable conditions expressed in the Operational Design Domain (ODD) of the truck platoon system and the planned operational environment.
OP-004	Performance measure(s) should capture the frequency of splits and re-joins that occur due to unequipped cut-in vehicles (considering actual gap between trucks) or middle platoon truck exits (if 3-truck platoon), categorized with respect to different conditions/environments encountered during trip.	This requirement ensures that measure(s) are developed to measure how the truck platoon system handles splits (ending platooning mode) and rejoins (restarting platooning mode) due to cut-ins or exits. A higher frequency of splits and rejoins (e.g., multiple splits/rejoins per mile) has the potential to become a nuisance to truck platoon drivers. It may also dissuade Fleet Operators from adopting truck platoon technology because it may negate potential fuel savings. Understanding the conditions that influence frequency of splits and re-joins may guide understanding on when and where platooning is more suitable.

2.2 Safety

Despite the potential benefits of truck platooning, there are still concerns regarding safety implications of implementing commercial truck platooning. Those concerns include platoon trucks not able to swiftly adapt to changing traffic conditions due to vehicle mechanics (e.g., brake performance of following truck), reduced visibility of following truck drivers (i.e., driver performance), highway hypnosis (i.e., truck drivers becoming over reliant on truck platoon system), and others (4) (11). Therefore, safety performance measures should be able to capture aspects of truck driver and truck performance that impact safety, as well as interactions with surrounding traffic. The requirements for safety performance measures are presented below in Table 2-2.

Table 2-2. Requirements for Safety Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
S-001	Performance measure(s) should capture how often platoon system notifies (or fails to notify) truck platoon drivers it is no longer controlling longitudinal gap and/or lateral movement and the reason(s) for such notifications.	This requirement ensures that measure(s) are developed to measure the frequency of instances where truck platoon drivers receive (or do not receive) notifications (which may be of varied types) from the truck platoon system that it is no longer controlling longitudinal and/or lateral movements of following trucks. The requirement also helps to understand the reasons for such notifications.
S-002	Performance measure(s) should capture how often platoon drivers disengage platoon system control and the reason(s) for such disengagements.	This requirement ensures that measure(s) are developed to measure the frequency of instances where truck platoon drivers exercise professional judgement by disengaging truck platoon system control. Also, it provides information about the reasons for such disengagements which allows assessment of safety-relevance.
S-003	Performance measure(s) should capture the number and types of platoon system failures (e.g., failure in coordinated braking between leading and following truck, V2V communication signal loss, malfunctioning radar/lidar, RF interference, etc.) as well as the conditions under which they occur.	This requirement ensures that measure(s) are developed to measure how often the truck platoon system fails. Examples of truck platoon system failures include failure in coordinated braking between leading and following trucks, V2V communication signal loss, RF interference, malfunctioning radar/lidar, etc.). The requirement also seeks information about the conditions under which truck platoon system failures occur. Potential conditions may include weather, roadway geometry, surrounding roadway environment (e.g., metallic environments may cause RF interference), etc.

ID	REQUIREMENT	EXPLANATION NOTES
S-004	Performance measure(s) should capture the overall reliability of the truck platoon system under different conditions as experienced.	This requirement ensures that measure(s) are developed to measure how reliable the truck platoon system is under different conditions. Reliability can be defined as the number of truck platoon system failures (e.g., failure in coordinated braking between leading and following trucks, V2V communication signal loss, RF interference, malfunctioning radar/lidar, etc.) as captured under S-003, expressed as a rate (e.g., trip/time/distance). The different conditions can include weather, roadway geometry, etc.
S-005	Performance measure(s) should capture truck driver fatigue (i.e., levels of drowsiness) under platoon and non-platoon modes using objective data.	Driving in a platoon presents challenges such as reduced forward vision of following trucks due to the small following gap. This may increase anxiety levels of following drivers which can eventually lead to increased or rapid fatigue as reflected in levels of drowsiness. This requirement ensures that measure(s) are developed to measure how the truck platoon system impacts driver fatigue using objective data. Objective data is data captured by the truck platoon system or independently captured by a monitoring system and excludes data provided by platoon truck drivers.

ID	REQUIREMENT	EXPLANATION NOTES
S-006	Performance measure(s) should capture truck platoon driver attentiveness / vigilance (e.g., influence on distraction) using objective data that captures the temporal aspects.	Platoon truck drivers are required to monitor the driving environment (e.g., they are required to maintain lateral control of trucks while in platoon mode) and be prepared to take over longitudinal control from the platoon system when the need arises. This requirement ensures that measure(s) are developed to measure whether drivers are being vigilant (identify changes in attention or distraction potential) using objective data that captures temporal aspects- both within trip (after different amounts of time spent platooning during a trip) and with platooning experience (after driver has used the system for many trips and has become more familiar/comfortable). Objective data is data captured by the truck platoon system or independently captured by a monitoring system and excludes data provided by platoon truck drivers.
S-007	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between the trucks in the platoon and the conditions under which they occur.	This requirement ensures that measure(s) are developed to measure the safety of trucks that travel in platoon mode under different conditions. Recognizing that crashes are rare and not anticipated in the field test, measures should be suited to the planned operational concept.

ID	REQUIREMENT	EXPLANATION NOTES
S-008	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and unequipped cut-in vehicles and the conditions under which they occur.	This requirement ensures that measure(s) are developed to measure the safety associated with interactions between platoon trucks and cut-in vehicles under different conditions. Recognizing that crashes are rare and not anticipated in the field test, measures should be suited to the planned operational concept.
S-009	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and surrounding traffic (excluding cut-in unequipped vehicles) and objects under different conditions.	This requirement ensures that measure(s) are developed to determine whether platoon trucks present safety concerns to surrounding traffic (excluding cut-in vehicles), objects, or due to roadway departures. Recognizing that crashes are rare and not anticipated in the field test, measures should be suited to the planned operational concept.
S-010	Performance measure(s) should capture the following truck's compliance with the system-defined minimum safe following gap considering truck load and roadway grade.	Trucks in a platoon, by design follow each other using a system-defined minimum safe following gap calculated based on truck speeds, braking performance, and other factors. This requirement ensures that measure(s) are developed to measure how following trucks consistently observe the minimum safe following gap under varying conditions such as load and grade.

ID	REQUIREMENT	EXPLANATION NOTES
S-011	Performance measure(s) should capture instances where platoon system initiates unnecessary collision avoidance (i.e., false positives).	It is unsafe for the truck platoon system to initiate collision avoidance actions when the driving environment doesn't call for it. Occurrence of such false positives may present safety issues to platoon trucks and surrounding traffic. This requirement ensures that measure(s) are developed to assess instances where false collision avoidance actions are initiated/reported.
S-012	Performance measure(s) should capture the accuracy with which the platoon trucks maintain the system's current set/target following gap(s) considering truck load and roadway grade.	Trucks in a platoon, depending on design, may follow each other using a driver-selected or system-selected set/target following gap calculated based on truck speeds, braking performance, and other factors. This requirement ensures that measure(s) are developed to measure how consistently the platoon actually maintains the gap(s) being targeted under varying conditions such as load and grade.

2.3 Mobility

Impacts of truck platooning on mobility (e.g., congestion and traffic flow) have been reported in many simulation studies and field experiments (5) (6). However, these studies are for limited controlled testing and do not cover varying roadway, weather, and operational conditions. The multi-state, long-haul field test of truck platooning operations provides an opportunity for a broader mobility impacts assessment. The requirements developed for mobility performance measures are as shown below in Table 2-3.

Table 2-3. Requirements for Mobility Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
M-001	Performance measure(s) should capture differences in travel time/travel time reliability of truck trips under platooning and non-platooning modes.	It is important to understand how the platoon system affects travel times/travel time reliability of platoon trucks. This requirement ensures that performance measures are developed to measure the impacts of truck platoon on truck travel times/travel time reliability especially as it pertains to on-time delivery performance of Fleet Operators.
M-002	Performance measure(s) should capture impacts of truck platoon on tactical behavior of surrounding traffic under different conditions (e.g., grades, travel lane, weather, etc.) encountered during trip.	This requirement ensures that performance measures are developed to measure how truck platoons affect tactical maneuvers of surrounding vehicles such as lane changing behavior, merging behavior, and speed. Classification by the conditions experienced may be necessary to understand the impacts to traffic.
M-003	Performance measure(s) should capture traffic flow impacts of truck platoons on deployment corridor under different conditions. Actual analysis may be performed by USDOT based on data provided by team.	This requirement ensures performance measures are developed to analyze the impacts of truck platoons on the transportation system under different conditions. The different conditions may include weather, traffic congestion levels, work zones, etc.

2.4 Energy and Emissions

One of the most promising benefits of truck platooning is energy savings (i.e., fuel savings) and reduction in truck vehicle emissions. The underlying idea is that trucks

traveling in close proximity would experience less aerodynamic drag and as a result consume less energy, depending on following distance (7) (8). Consequently, reductions in fuel use can lead to potential reductions in emissions. The requirements developed for performance measures that capture the impacts of truck platooning on energy use and emissions are presented below in Table 2-4.

Table 2-4. Requirements for Energy and Emissions Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
EE-001	Performance measure(s) should capture changes in fuel use due to truck platoons under different gap settings, truck configurations, load levels, and external conditions using objective data as experienced during trip.	With trucks in a platoon traveling at closer distance gaps, the effect of aerodynamic drag may be reduced and eventually lead to reductions in fuel use. This requirement ensures that performance measure(s) are developed to measure the impacts of truck platoons on fuel use under conditions experienced during trip (e.g., platoon mode status, varying gap settings, truck configurations, loading levels, and external conditions) using objective data. Objective data is data captured by the truck platoon system or independently captured by a monitoring system and excludes data provided by platoon truck drivers. Example of an objective data is fuel meter data.
EE-002	Performance measure(s) should capture changes in emission levels due to truck platoons under different gap settings, truck configurations, load levels and external conditions.	With trucks in a platoon traveling at closer distance gaps, the effect of aerodynamic drag may be reduced and eventually lead to reductions in fuel use. This requirement ensures that performance measure(s) are developed to assess the impacts of truck platoons on emission levels under conditions experienced during trip (e.g., platoon mode status, varying gap settings, truck configurations, loading levels, and external conditions).

2.5 Fleet Operator and Truck Driver Impacts

During the steady-state cruising phase of truck platooning system with SAE Level 1 automation capabilities, driver performance will mostly consist of steering

performance while travelling at shorter following gaps. Because drivers of following trucks have reduced visibility of the roadway ahead due to the shorter following gaps, it is possible that a truck driver's steering workload will be increased — especially in curves — leading to more rapid fatigue and decreased vigilance over time. For truck platooning technology to be accepted by truck drivers, they need to be educated on capabilities of the specific truck platooning implementation as well as the potential additional driving responsibilities. In addition to impacts of truck platooning on truck drivers, fleet operators may have to adjust their daily operations to accommodate (e.g., loading multiple trucks at a time to enable depart depot/warehouse at the same time) some of the requirements needed for commercial truck platooning to be effective. The requirements for performance measures that capture the impacts of truck platooning on fleet operators and truck drivers are presented in Table 2-5 below.

Table 2-5. Requirements for Fleet Operator and Truck Driver Impacts Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
FLT-001	Performance measure(s) should capture impacts of truck platooning on Fleet Operators daily operations	Adopting truck platoon technology may affect the daily operations of Fleet Operators, such as impacting amount of time truck drivers and dispatchers spend, logistics impacts, subjective/qualitatively measured impacts, etc. This requirement ensures that performance measure(s) are developed to measure the impacts of adopting truck platoon technology on the daily operations of Fleet Operators.
FLT-002	Performance measure(s) should capture cost savings to fleet operators due to fuel efficiency gains	This requirement ensures that performance measure(s) are developed to measure Fleet Operators' cost savings due to truck platoons.

ID	REQUIREMENT	EXPLANATION NOTES
FLT-003	Performance measure(s) should capture impacts of training on truck platoon drivers performance as well as Fleet Operators operations.	This requirement ensures that performance measures are developed to measure how training of drivers affect their understanding, safe operation, and eventual acceptance of the truck platoon system. This does not imply providing different or no training; however, if there are needs for re-training from driver misunderstandings of system operation, not adhering to instructions, etc. encountered during operation, that should be captured. The requirement also seeks to understand how the training activities affect Fleet Operators operations. For example, the number of training activities may affect truck drivers availability to complete actual trips.
FLT-004	Performance measure(s) should capture how drivers adapt to the truck platoon system over time.	This requirement ensures that performance measures are developed to measure the learning curve of truck platoon drivers. It looks at both positive and negative adaptations over time, i.e., within trip (beginning vs. end of platoon trip), and longer term (when inexperienced with platoon system vs. after many platooning trips), as experienced by drivers.
FLT-005	Performance measure(s) should capture driver acceptance/satisfaction of/with truck platoon technology taking into account driver's position in the platoon.	This requirement ensures that performance measures are developed to measure the overall driver perception/view of the truck platooning system after using it during the deployment period.

ID	REQUIREMENT	EXPLANATION NOTES
FLT-006	Performance measure(s) should capture Fleet Operators' acceptance/satisfaction of/with truck platoon technology.	This requirement ensures that performance measures are developed to measure the overall Fleet Operators' perception about truck platoon technology after using it during the deployment period. This covers any other acceptance factors beyond direct operational impacts in FLT-001.
FLT-007	Performance measure(s) should capture how truck platoons affects driver behavior (e.g., highway following gap) in non-platoon situations.	This requirement ensures that performance measures are developed to measure the behavior of truck platoon drivers when they drive in non-platoon mode within trips and over longer time, as experienced. For example, this covers if drivers tend to shorten following distances in normal non-platoon driving after becoming comfortable with the platooning operation.

2.6 Infrastructure Impacts

Truck platooning may not be practical on all the different types of roadway infrastructure. It is important to identify infrastructure characteristics and requirements that would support safe and extended performance (i.e., ability to platoon on long continuous stretches of roadway) of truck platoons. Infrastructure characteristics such as facility types, roadway geometry (horizontal/vertical curves), number of lanes, dedicated lanes, speed limits, bridge crossing restrictions, and others, may influence the operational design domain of truck platoon systems. Therefore, it is important to determine infrastructure and roadway characteristics that may/may not permit safe and beneficial operation of truck platoons. Additionally, close following between trucks in a platoon and corresponding dynamic behavior (e.g., loading levels, acceleration, etc.) may affect the structural health of roadway infrastructure such as bridges (9) and pavements. The requirements for infrastructure impacts performance measures are shown below in Table 2-6.

Table 2-6. Requirements for Infrastructure Impacts Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
II-001	Performance measures should capture the impact of truck platoon on bridge structures. Actual analysis may be performed by USDOT based on data provided by team.	This requirement ensures that performance measures are developed to enable analysis of how the characteristics of platoon trucks (e.g., platoon truck spacing, axle spacing/loads, truck weight, load/trailer configurations, braking/acceleration profiles, etc.) as experienced, affect the structural health of bridges.
II-002	Performance measure(s) should capture information on infrastructure configuration/characteristics suitable for truck platoons and vice versa, as experienced during trip.	This requirement ensures that performance measures are developed to understand which infrastructure configurations (e.g., lane, ramp configurations) and conditions (e.g., pavement conditions) are suitable for truck platooning operations. The intent is not to alter the system's ODD but to assess behavior and performance under conditions that are experienced (e.g., where truck drivers choose to disengage due to infrastructure conditions/configurations). Note that influence of traffic as a primary factor is covered in conditions in OP-003.
II-003	Performance measure(s) should capture impacts of truck platoon on roadway pavements. Actual analysis may be performed by USDOT based on data provided by team.	This requirement ensures that performance measures are developed to enable analysis of the impacts of truck platoon (e.g., influence on truck driver's or platoon system's lateral tracking offset between trucks) on the structural health of roadway pavements.

2.7 State and Local Government Impacts

Introduction of truck platoons on public roads implies possible changes to the way transportation systems are managed at the state and local levels from both an operational and law enforcement standpoint (e.g., following distance laws). Three requirements were initially developed for this key area. However, based on feedback from the Phase 1 Awardees and FHWA, the second requirement (SL-002) was removed. The requirements for performance measures with respect to the impacts of truck platooning on state and local governments are as shown below in Table 2-7.

Table 2-7. Requirements for State and Local Government Impacts Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
SL-001	Performance measure(s) should capture interactions between truck platoon drivers and law enforcement officials, such as regarding states' safe following distance laws.	This requirement ensures that performance measures are developed to capture instances where law enforcement officials pull over platoon trucks, if experienced. It is assumed that the deployment teams will choose routes whose safe following distances can be adhered to by their truck platoon system. However, there might be instances where law enforcement officials will mistakenly identify trucks in platoon mode as tailgating. Capturing logs of experiences and lessons learned from any interactions could help future guidance.
SL-003	Performance measure(s) should capture impacts/differences (if any) in truck inspection and enforcements for truck platooning	This requirement helps understand how inspections and enforcement of laws are conducted while trucks travel in a platoon trip, including any specific inspection differences (e.g., selection for inspection) and impacts for platoon-equipped truckers/drivers (e.g., how will an inspection delay for one truck in a platoon impact the other truck(s) in the platoon). The requirement also seeks to understand any potential equipment, training, or practices needed by law enforcement officials to conduct inspections of platoon trucks in the future, by documenting interactions as experienced in the project.

2.8 Vehicle Equipment Design Implications

As a new technology, truck platoon technology will require the acceptance of truck drivers and fleet operators/owners for it to be commercially viable. The acceptance includes (but is not limited to) ease of use of the truck platoon technology, truck driver comfort levels with the technology, reliability of the technology, etc. Based on these feedback, potential designs for improved safety, reliability, and effective

performance can be considered. The requirements for vehicle equipment design implications performance measures is presented below in Table 2-8.

Table 2-8. Requirements for Vehicle Equipment Design Implications Performance Measures

ID	REQUIREMENT	EXPLANATION NOTES
VED-001	Performance measure(s) should provide information regarding truck drivers opinions on truck platoon equipment design deficiencies observed during the deployment	This requirement ensures that performance measures are developed to capture truck platoon equipment design deficiencies and lessons learned as observed by truck drivers/fleet operators during field operation.
VED-002	Performance measure(s) should capture the reliability of V2V communications between trucks in a platoon.	This requirement ensures that performance measures are developed to measure the reliability of the critical enabling communications between truck platoon leader and follower(s) for environments experienced during trip.
VED-003	Performance measure(s) should capture the effectiveness of information provided to drivers of following trucks (e.g., forward video streamed from lead to following truck, other DVI).	This requirement ensures that performance measures are developed to measure how information received by following truck drivers affect their driving performance/driving task and are perceived by truck drivers.

2.9 Prioritization of Requirements

Based on feedback from Phase 1 Awardees as well as the potential funding limits for Phase 2 of this project, there was a need to assign priority levels to each of the requirements developed for performance measures. In general, “prioritizing requirements” can have very different meanings to different stakeholders (10). In this project, prioritization deals with relative importance of the many requirements

developed. That is, per the goals and objectives of this project, some requirements merit attention (i.e., need to be addressed) before other competing requirements are attended to (if budget and time allows). The prioritization of requirements in this project was based on the preference of the ITS JPO and its partner agencies (primarily FHWA, NHTSA, FMCSA, and DOE) in terms of value of the insights associated with the respective requirements. Three main priority levels were defined, and each requirement was assigned one of these priority levels. The three priority levels and their general definitions are as follows:

- **Most Important:** If a requirement for performance measures is assigned "most important" priority, it implies that developing performance measures to satisfy those requirements is of topmost priority. In other words, ITS JPO and its partner agencies (primarily FHWA, NHTSA, FMCSA, and DOE) expect to gain valuable insights regarding that aspect of truck platooning from this project.
- **Important:** A requirement for performance measure(s) with "important" designation implies consideration should be given to developing performance measures to satisfy that requirement. While insights from requirements in this priority level are valuable they are of a second level of importance.
- **Desirable:** A requirement for performance measure(s) with "desirable" priority level implies that performance measures may be developed for such requirement; however, they are "nice-to-haves" and not of highest value as far as this project is concerned.

Although each requirement was assigned a priority level, the Awardees have the flexibility to choose which of the requirements they intend to satisfy in Phase 2. The decision on which requirements to satisfy will depend on factors such as Awardees' proposed truck platooning concept, cost of data collection, cost of developing performance measure(s) to satisfy requirements versus value trade-off, etc. Also, there is no restriction on the number of requirements or mix of requirements (i.e., considering priority levels) that Awardees must satisfy.

It is worth noting that the priority levels assigned to requirements in this report are tied to the goals and objectives of this project. In a different truck platooning project, different priority levels may be assigned to these requirements depending on the goals and objectives of the individual project. Table 2-9 below presents the priority level for each of the requirements developed in this project.

Table 2-9. Requirements for Performance Measures and Priority Levels for Phase 2 of USDOT Level 1 Truck Platooning Assessment Project

ID	Requirements	Priority for Phase 2
OP-001	Performance measure(s) should capture how long it takes for truck platoon to be formed based on the choice of coordination strategy being used and other factors.	Important
OP-002	Performance measure(s) should capture general behavior of trucks/drivers (e.g., speeding behavior, lane changing behavior, etc.) as they seek to form a platoon.	Most Important
OP-003	Performance measure(s) should capture the usage rate of truck platoon system categorized with respect to different conditions/factors encountered during trips.	Most Important
OP-004	Performance measure(s) should capture the frequency of splits and re-joins that occur due to unequipped cut-in vehicles (considering actual gap between trucks) or middle platoon truck exits (if 3-truck platoon), categorized with respect to different conditions/environments encountered during trip.	Most Important
S-001	Performance measure(s) should capture how often platoon system notifies (or fails to notify) truck platoon drivers it is no longer controlling longitudinal gap and/or lateral movement and the reason(s) for such notifications.	Important
S-002	Performance measure(s) should capture how often platoon drivers disengage platoon system control and the reason(s) for such disengagements.	Most Important
S-003	Performance measure(s) should capture the number and types of platoon system failures (e.g., failure in coordinated braking between leading and following truck, V2V communication signal loss, malfunctioning radar/lidar, RF interference, etc.) as well as the conditions under which they occur.	Most Important

ID	Requirements	Priority for Phase 2
S-004	Performance measure(s) should capture the overall reliability of the truck platoon system under different conditions as experienced.	Most Important
S-005	Performance measure(s) should capture truck driver fatigue (i.e., levels of drowsiness) under platoon and non-platoon modes using objective data.	Most Important
S-006	Performance measure(s) should capture truck platoon driver attentiveness / vigilance(e.g., influence on distraction) using objective data that captures the temporal aspects.	Most Important
S-007	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between the trucks in the platoon and the conditions under which they occur.	Most Important
S-008	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and unequipped cut-in vehicles and the conditions under which they occur.	Most Important
S-009	Performance measure(s) should capture rates of crashes, near-crashes, and crash-relevant conflicts (including safety-critical events) between platoon trucks and surrounding traffic (excluding cut-in unequipped vehicles) and objects under different conditions.	Most Important
S-010	Performance measure(s) should capture the following truck's compliance with the system-defined minimum safe following gap considering truck load and roadway grade.	Most Important
S-011	Performance measure(s) should capture instances where platoon system initiates unnecessary collision avoidance (i.e., false positives).	Important

ID	Requirements	Priority for Phase 2
S-012	Performance measure(s) should capture the accuracy with which the platoon trucks maintain the system's current set/target following gap(s) considering truck load and roadway grade.	Most Important
M-001	Performance measure(s) should capture differences in travel time/travel time reliability of truck trips under platooning and non-platooning modes.	Desirable
M-002	Performance measure(s) should capture impacts of truck platoon on tactical behavior of surrounding traffic under different conditions (e.g., grades, travel lane, weather, etc.) encountered during trip.	Important
M-003	Performance measure(s) should capture traffic flow impacts of truck platoons on deployment corridor under different conditions. Actual analysis may be performed by USDOT based on data provided by team.	Desirable
EE-001	Performance measure(s) should capture changes in fuel use due to truck platoons under different gap settings, truck configurations, load levels, and external conditions using objective data as experienced during trip.	Most Important
EE-002	Performance measure(s) should capture changes in emission levels due to truck platoons under different gap settings, truck configurations, load levels and external conditions.	Desirable
FLT-001	Performance measure(s) should capture impacts of truck platooning on Fleet Operators daily operations	Desirable
FLT-002	Performance measure(s) should capture cost savings to fleet operators due to fuel efficiency gains	Desirable

ID	Requirements	Priority for Phase 2
FLT-003	Performance measure(s) should capture impacts of training on truck platoon driver's performance as well as Fleet Operators operations.	Desirable
FLT-004	Performance measure(s) should capture how truck drivers adapt to the truck platoon system over time.	Important
FLT-005	Performance measure(s) should capture driver acceptance/satisfaction of/with truck platoon technology taking into account truck driver's position in the platoon.	Most Important
FLT-006	Performance measure(s) should capture Fleet Operators' acceptance/satisfaction of/with truck platoon technology.	Most Important
FLT-007	Performance measure(s) should capture how truck platoons affects truck driver behavior (e.g., highway following gap) in non-platoon situations.	Most Important
II-001	Performance measures should capture the impact of truck platoon on bridge structures. Actual analysis may be performed by USDOT based on data provided by team.	Most Important
II-002	Performance measure(s) should capture information on infrastructure configuration/characteristics suitable for truck platoons and vice versa, as experienced during trip.	Important
II-003	Performance measure(s) should capture impacts of truck platoon on roadway pavements. Actual analysis may be performed by USDOT based on data provided by team.	Desirable
SL-001	Performance measure(s) should capture interactions between truck platoon drivers and law enforcement officials, such as regarding states' safe following distance laws.	Most Important

ID	Requirements	Priority for Phase 2
SL-003	Performance measure(s) should capture impacts/differences (if any) in truck inspection and enforcements for truck platooning	Desirable
VED-001	Performance measure(s) should provide information regarding truck driver's opinions on truck platoon equipment design deficiencies observed during the deployment	Important
VED-002	Performance measure(s) should capture the reliability of V2V communications between trucks in a platoon.	Most Important
VED-003	Performance measure(s) should capture the effectiveness of information provided to drivers of following trucks (e.g., forward video streamed from lead to following truck, other DVI).	Important

3 Conclusions

This report is an outcome of the Phase 1 IE's support to ITS JPO and its partner agencies (primarily FHWA and FMCSA) on the "Truck Platooning Early Deployment Assessment, Phase 1" project. The report includes:

- Requirements for performance measures to guide the development of performance measures and evaluation plans thereof by Phase 1 Awardees, and eventually the evaluation of Phase 2 field test(s); and
- Levels of priority associated with each of the developed requirements based on the goals and objectives of this project.

While the requirements for performance measures developed in this project can be used to guide performance evaluation of other truck platooning projects, it is imperative that they are adapted to suit the specific goals and objectives of the individual project. However, the priority levels associated with performance measure requirements must be developed from scratch based on the specific goals and objectives of the individual project.

This report documents what has been done so far in this project. The requirements for performance measures developed will be used by Phase 1 Awardees to develop performance measures that will be used to evaluate the performance and impacts of truck platooning field operational test to be conducted in Phase 2.

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ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

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